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History Propagation

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Vertical ionospheric sounding: a technique to measure the electronic density in the ionosphere.

Electromagnetic waves, radio and the ionosphere

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- Brief History related to the ionospheric measurements

- Radio wave propagation

- Plasma-wave interaction

- Measurements techniques (Radio & radar principles)

- Doppler shift measurements

Electromagnetic waves, radio and ionosphere

- The history of the radio and the related devices is strictly connected to ionospheric measurements. Later, the knowledge of the radio wave propagation contributed to determine the existence of the ionosphere and its complex structure
- 1862-James Clerk Maxwell completes the foundations of classical electrodynamics by adding the displacement current in Ampere's law. This theory, which was later presented in the form of the four Maxwell's equations, predicts electromagnetic waves.
- 1888 - Heinrich Hertz produces the first electro-magnetic waves. He was able to radiate electromagnetic waves and measure the wavelength and velocity of these so-called Hertzian waves.

1895 - Marconi develops a practical apparatus comprising an aerial, a condenser and a connection to ground (first practical radio).

1901- Communication across the Atlantic

1902- Kennelly and Heaviside say that the wave propagation is supported by a conducting layer that acts like a reflector

1902- Hulsmayer develops the first interferometric radar (2-3 km range)

1904 John Ambrose Fleming invents the diode

1906 - De Forest adds a third electrode to the diode and produces a sensitive receiver and amplifier.

1912- Edwin H. Armstrong introduces the positive feedback (starting from this spectral pure waves were generated by simple oscillators)

1913- R.A. Heising invents the superheterodyne receiver

1924- Larmor (following Eccels) derives some important theoretical results for a collisional medium

(1925) Breit and Tuve make a pulsed transmitter in order to measure delays of vertically reflected pulses by means of an oscillograph. The reflection height is simply obtained from the delay time and the speed of light. This experiment works as a model for the future ionosondes and also eventually contributes to the development of the radar.

1926- Appleton and Barnett apply two different methods based on continuous transmission. In the first one the elevation angle of the signal arriving at the receiver is measured and, when the distance between the transmitter and the receiver is known, the altitude of the reflecting layer can be calculated.
In the second method the receiver is close to the transmitter and changes in the interference pattern of the ground wave and a nearly vertically reflected wave are observed when the transmitting frequency is slowly varied.

1927- H.S. Black develops the negative feedback
(automatic gain control AGC)

1927-1932 -Lassen, Appleton, Hartree and Altar present the theory for the dispersion of the electromagnetic wave in a medium such as the ionosferic plasma. It is an equation of the magneto plasma refractive index.

$$n^2 = 1 - \frac{X}{1 - jZ - \frac{{Y_T}^2}{2(1 - X - jZ)} \pm \sqrt{\frac{{Y_T}^4}{(1 - X - jZ)^2} + {Y_L}^2}}$$

Rawer and Suchy (1976) demonstrate that Hartree formulation is not correct and the correct dispersion equation was really published for the first time in a somewhat different form by Lassen (1927). In the previous period W. Altar has frequent contacts with Appleton. In his letters Altar derives the tensorial method for a magnetoplasma.

Electromagnetic wave –magnetoplasma interaction

- The theory is described by the formula of Appleton-Lassen (to not to mention Altar and Hartree) that is a high-frequency approximation of electro-magnetic waves in cold magnetoplasma.

The theory does not take into account the velocity distribution of the electrons and it approximates the damping due to the collisions of electrons with the neutrals by introducing a friction term controlled by a single collision frequency.

The formula gives two values of the complex refractive index for each frequency, one corresponding to the plus and the other to the minus sign in the denominator.

This means that two modes of electromagnetic waves exist in a magnetoplasma so that the medium is bi-refractive. The modes are usually called the ordinary (o) and extraordinary (x).

Propagation of the Radio Wave

Electromagnetic Waves

- In order to give a better understanding of the ionospheric measurements by means of ionosonde (HF-radar) or other radio techniques, it is useful to give a short description of the electromagnetic radiation (e.m. wave). Electromagnetic wave consists of time oscillating electric and magnetic fields in certain directions able to propagate into space.

Electromagnetic Radiation

- Includes radio waves, light, X-rays, gamma rays

Radio waves of our interest

VLF	**3 – 30**	kHz
LF	**30 – 300**	kHz
MF	**300 – 3000**	kHz
HF	**3 – 30**	MHz
VHF	**30 – 300**	MHz
UHF	**300 – 3000**	MHz

Maxwell's Equations

1) div $\mathbf{E} = \rho/\varepsilon_0$

2) div $\mathbf{B} = 0$

3) rot $\mathbf{E} = -\, \partial\mathbf{B}/\partial t$

4) rot $\mathbf{B} = \varepsilon\, \mu\, \partial\mathbf{E}/\partial t + \mu\mathbf{J}$

Wave equation

By applying the operator $\vec{\nabla}$ on the third of the Maxwell's equations

$$\vec{\nabla}\times\left(\vec{\nabla}\times\vec{E}\right)=-\vec{\nabla}\times\frac{\partial\vec{B}}{\partial t}$$

In the above, the first member can be substituted by the following therefore exploiting the vector identity

$$\vec{\nabla}\times\left(\vec{\nabla}\times\vec{E}\right)=-\nabla^{2}\vec{E}+\vec{\nabla}\cancel{\left(\vec{\nabla}\cdot\vec{E}\right)}$$

$$\nabla^{2}\vec{E}=\vec{\nabla}\times\frac{\partial\vec{B}}{\partial t}$$

Wave equation

Exchanging the order of spatial and temporal derivative in the second member of the previous equation we obtain:

$$\nabla^2 \vec{E} = \varepsilon_0 \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

The structure of this equation was well known by Maxwell because D'Alembert solved a similar equation for the vibrating string.

Wave equation

$\partial^2 g/ \partial x^2 = 1/v^2 (\partial^2 g/ \partial t^2)$ wave equation

$y = f(x-vt)$ *towards x*

$y = f(x+vt)$ *opposed to x*

$v = dx/dt$ phase *velocity*

Sinusoidal Wave

$$\mathbf{y = A\ sen\ [kx - \omega t)]}$$
$$\mathbf{y = A\ cos\ [kx - \omega t)]}$$

λ wavelength
ν frequency
$k = 2\pi/\lambda$ wave number
$\omega = 2\pi/T$ pulsation

$$\mathbf{v} = \lambda \nu$$

Propagation

Given the system of Maxwell's equations the wave equation is nearly direct and it is easy to demonstrate that E and B are transversal. Moreover E/B=c.

$$E=E_{max}\cos(\omega t- kx)$$

$$B=B_{max}\cos(\omega t- kx)$$

Such equation can be written in terms of complex exponential as:

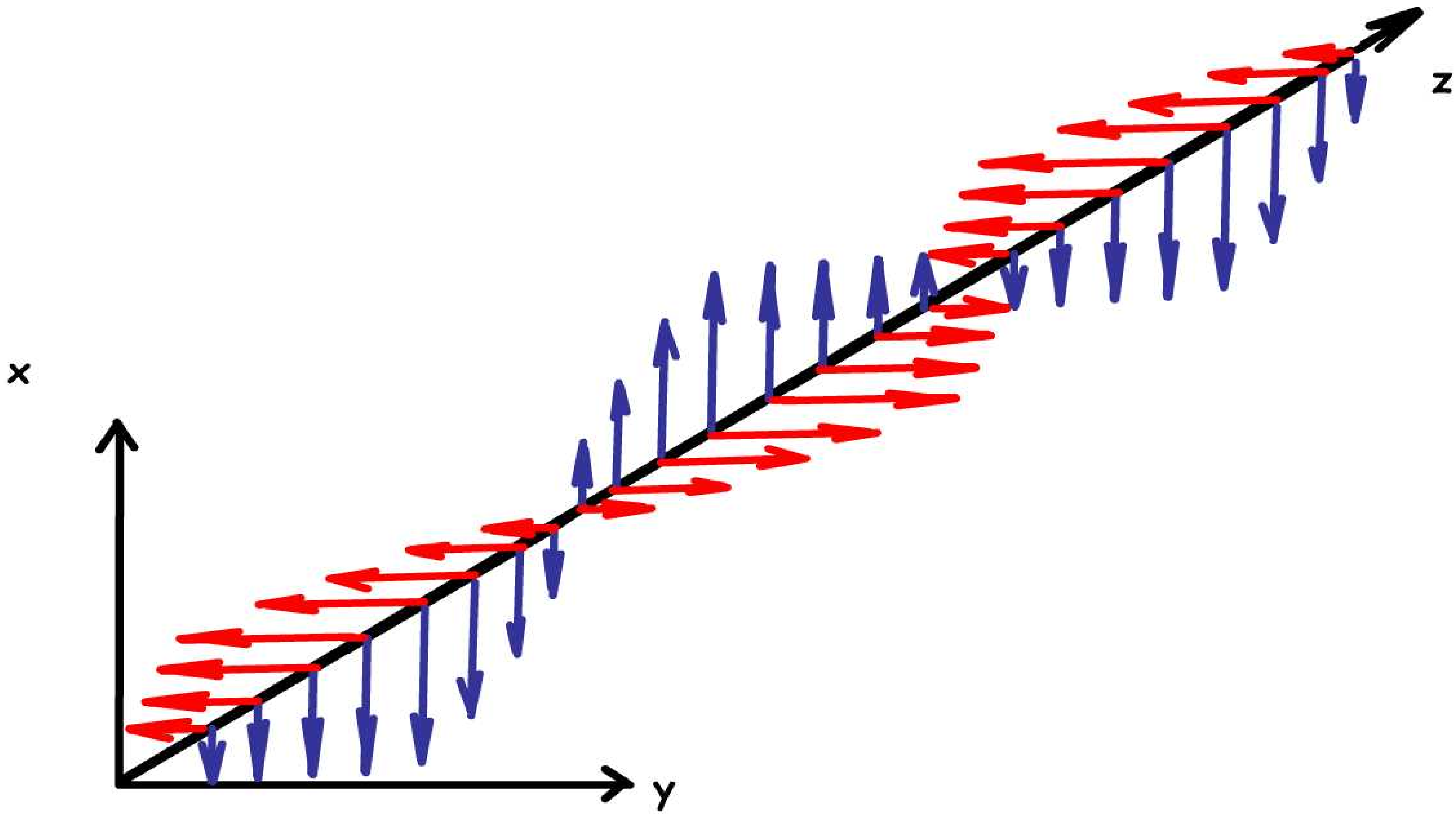
$$E=E_{max}e^{j(\omega t- kx)}$$

$$B=B_{max}e^{j(\omega t- kx)}$$

Remember the Euler's identity

$$e^{jx}=\cos(x)+j\sin(x)$$

Onda TEM che si propaga lungo z



TEM Propagation

- Radio waves in space are transverse electromagnetic waves (TEM)
- Electric field, magnetic field and direction of travel of the wave are mutually perpendicular
- Waves will propagate through free space and dielectrics
- Conductors have high losses due to induced current

Propagation Velocity

- Speed of light in free space: 3×10^8 m/s
- In dielectric and plasma the velocity of propagation is lower:

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

Electric and Magnetic Fields

- For waves we use the following units:

  – Electric field strength **E** (V/m)
  – Magnetic induction **B** (V.s/m^2)

  - Magnetic field strength **H** (A/m)

  - Power density P_D (W/m^2)

Ohm's Law in Space

$$Z = E / H$$

– Characteristic impedance Z in a medium is given by Ohm's law.

– For free space, Z = 377 Ohm

Power Density

$$P_D = \frac{E^2}{Z}$$

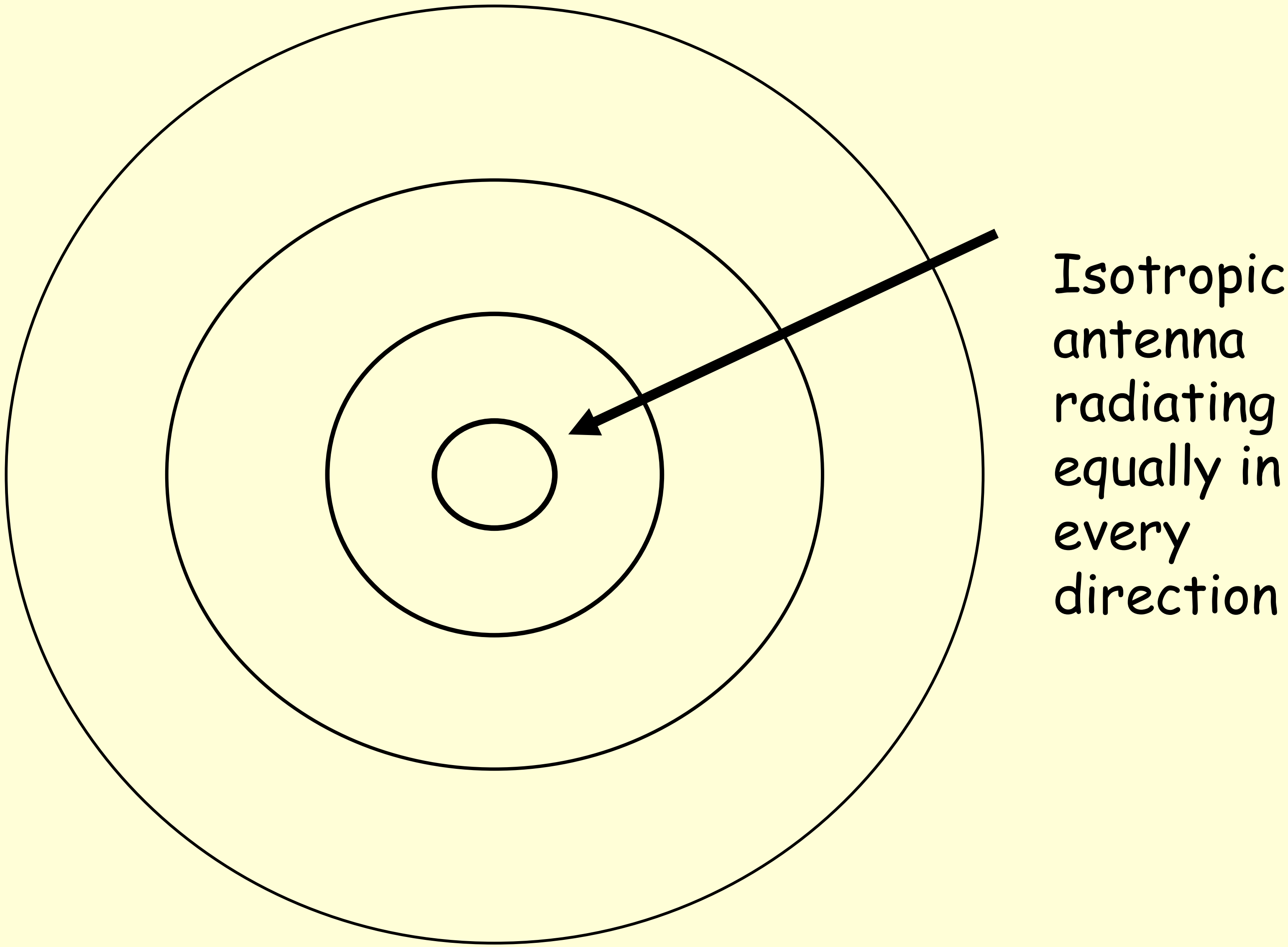
$$= H^2 Z$$

$$= EH$$

Plane and Spherical Waves

- Waves from a point in space are spherical
- Plane waves are easier to analyse
- At a reasonable distance from the source, spherical waves look like plane waves, as long as only a small area is observed

Spherical waves

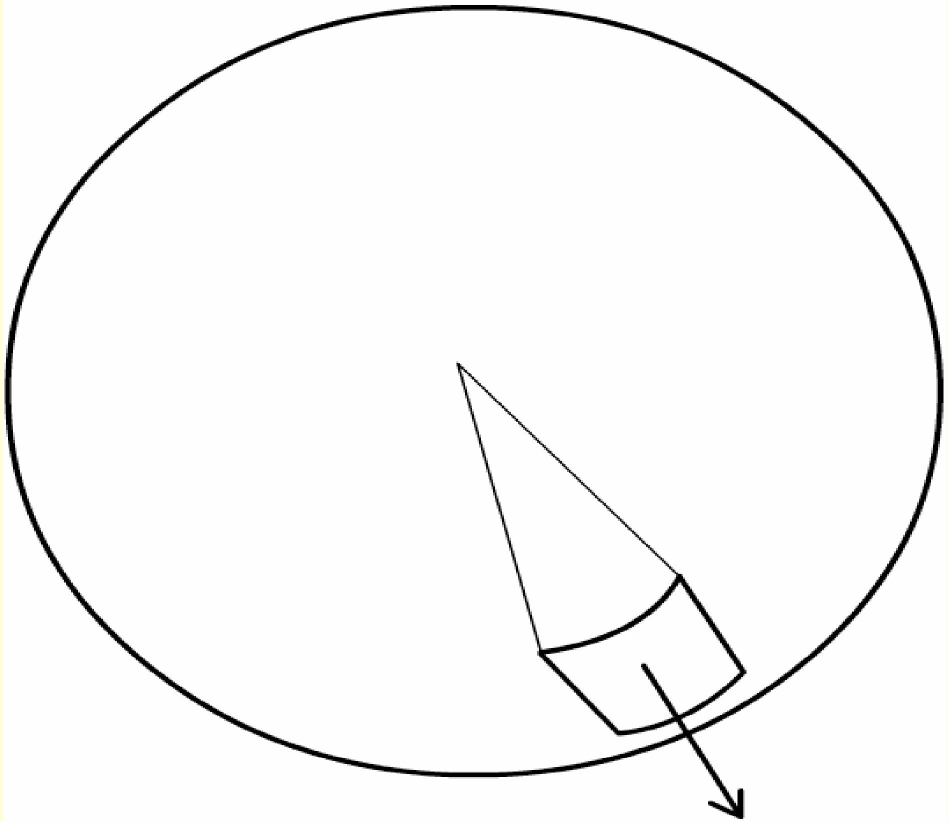


Free-space Propagation

- Assume an isotropic radiator at the center of a sphere
- Let the receiving antenna be on the surface of a sphere
- As we move farther from the transmitter the amount of power going through the surface remains the same but surface area increases

Power flux density

Power flux density= **E** × **H**



Geometrical loss

Because of the power P on the spherical surface is constant for every spherical surface ($4\pi r^2$) we consider, the power flux density at the distance r from the isotropic antenna must decrease as $1/4\pi r^2$.

$$P_D = \frac{P}{4\pi r^2}$$

If an isotropic antenna radiates 10 W of power at the distance of 1 km the power flux density (P_D)is about 0.796 $\mu W/m^2$

Attenuation of Free Space

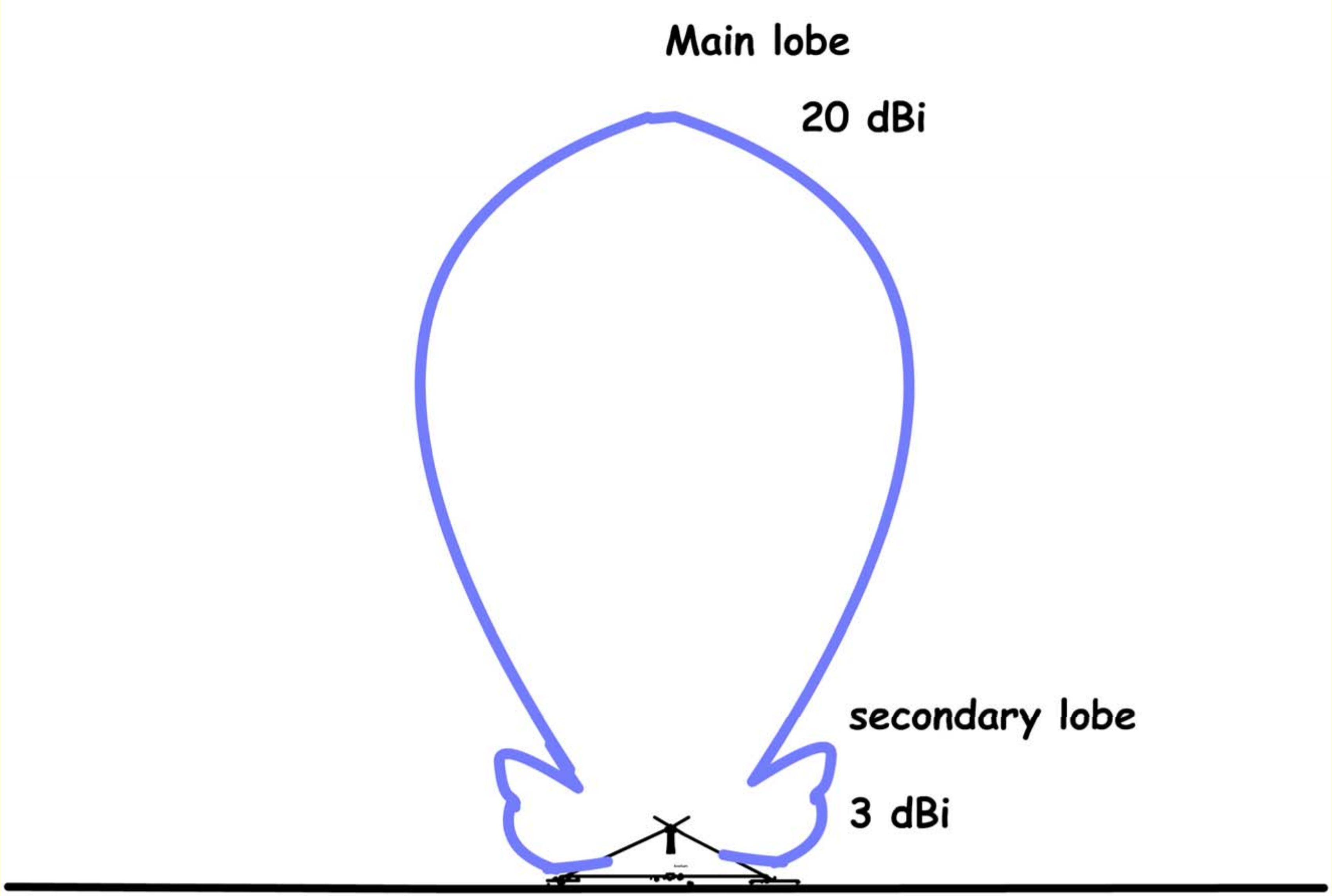
- Power stays the same but power density is reduced with increasing distance r
- Power density is total power divided by surface area of sphere
- Unit: watts/meter^2

$$P_D = \frac{P_t}{4\pi r^2}$$

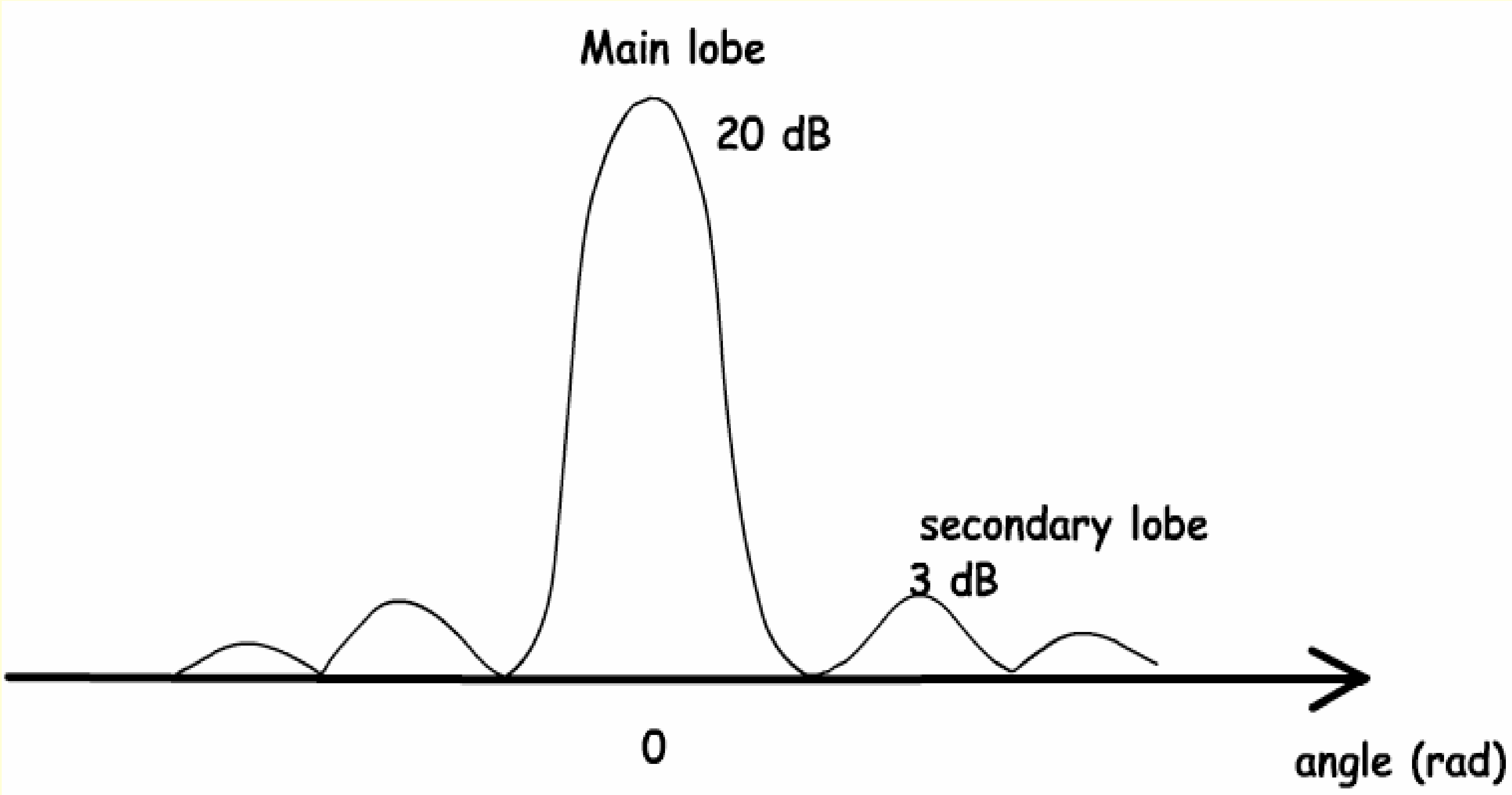
Transmitting Antenna Gain (G)

- Gain is achieved by radiating more energy in some directions than others
- Total radiated power cannot be more than power input to antenna
- Gain is usually expressed with reference to an isotropic radiator
- By definition $G = P_D/P$ (Isotropic radiator)

Antenna gain



Antenna gain 2-D



Power Density at distance r including antenna Gain

$$P_D = \frac{P_T G_T}{4\pi r^2}$$

Receiving Antenna Effective Area

- The receiving antenna can be considered to absorb all the power passing through a certain area
- This is the antenna's *effective area*
- Effective area is related to wavelength and gain

Calculation of Effective Area

$$A_{eff} = \frac{\lambda^2 G_R}{4\pi}$$

Received Power

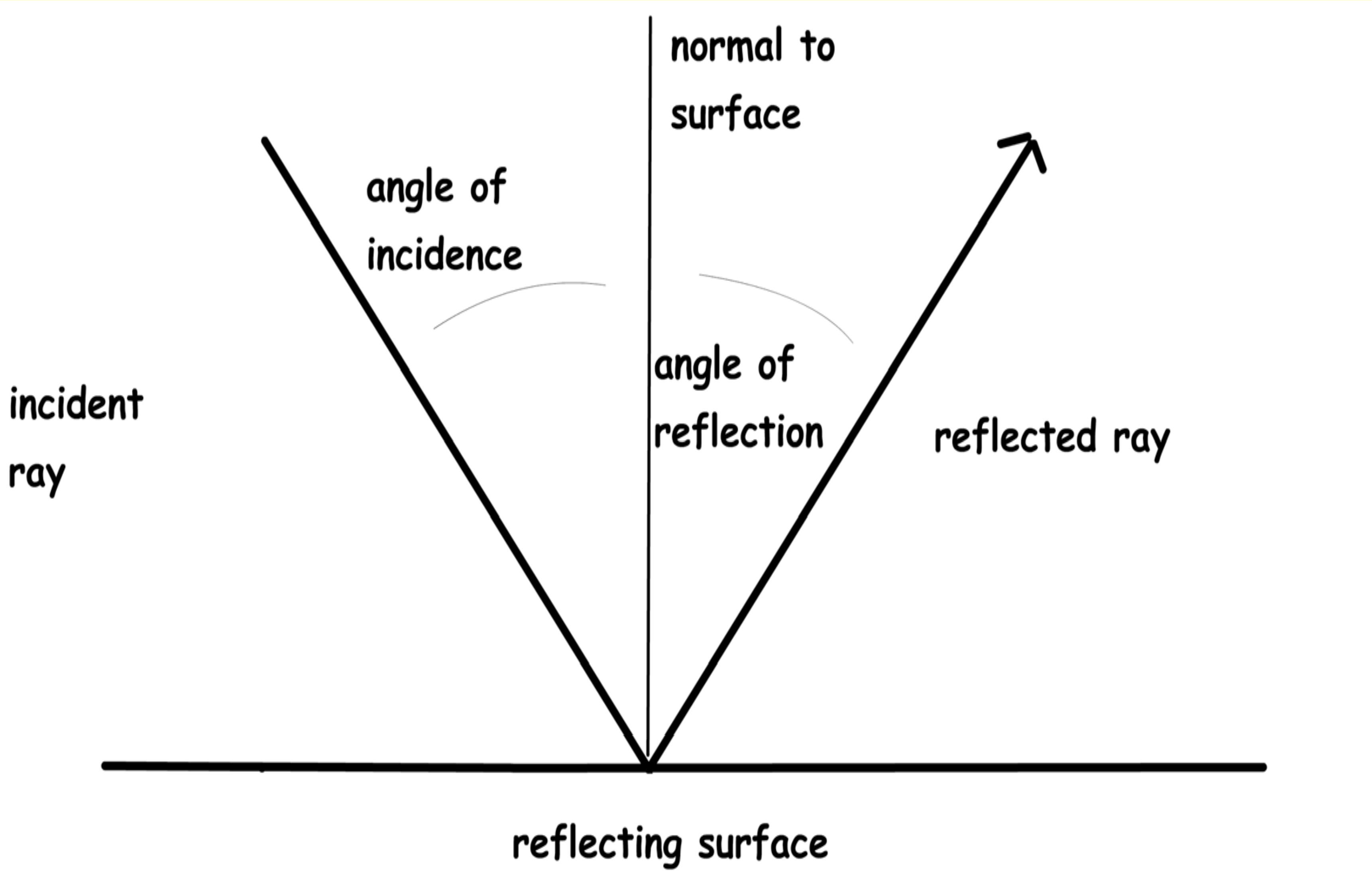
$$P_R = A_{eff} P_D$$

$$= \frac{A_{eff} P_T G_T}{4\pi r^2}$$

Reflection

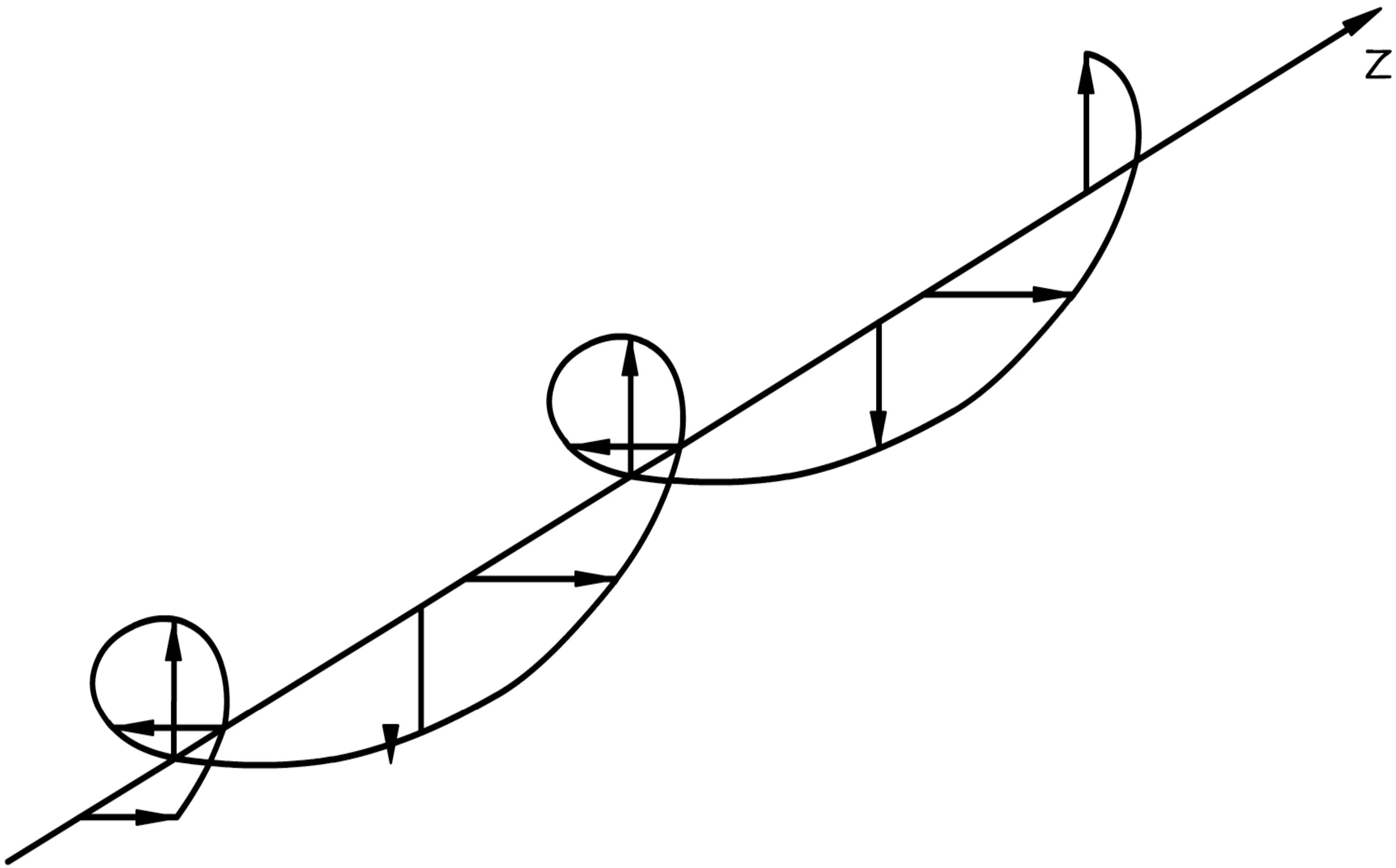
- Specular reflection: smooth surface
  - Angle of incidence = angle of reflection
- Diffuse reflection: rough surface
  - Reflection in all directions because angle of incidence varies over the surface due to its roughness

Specular Reflection

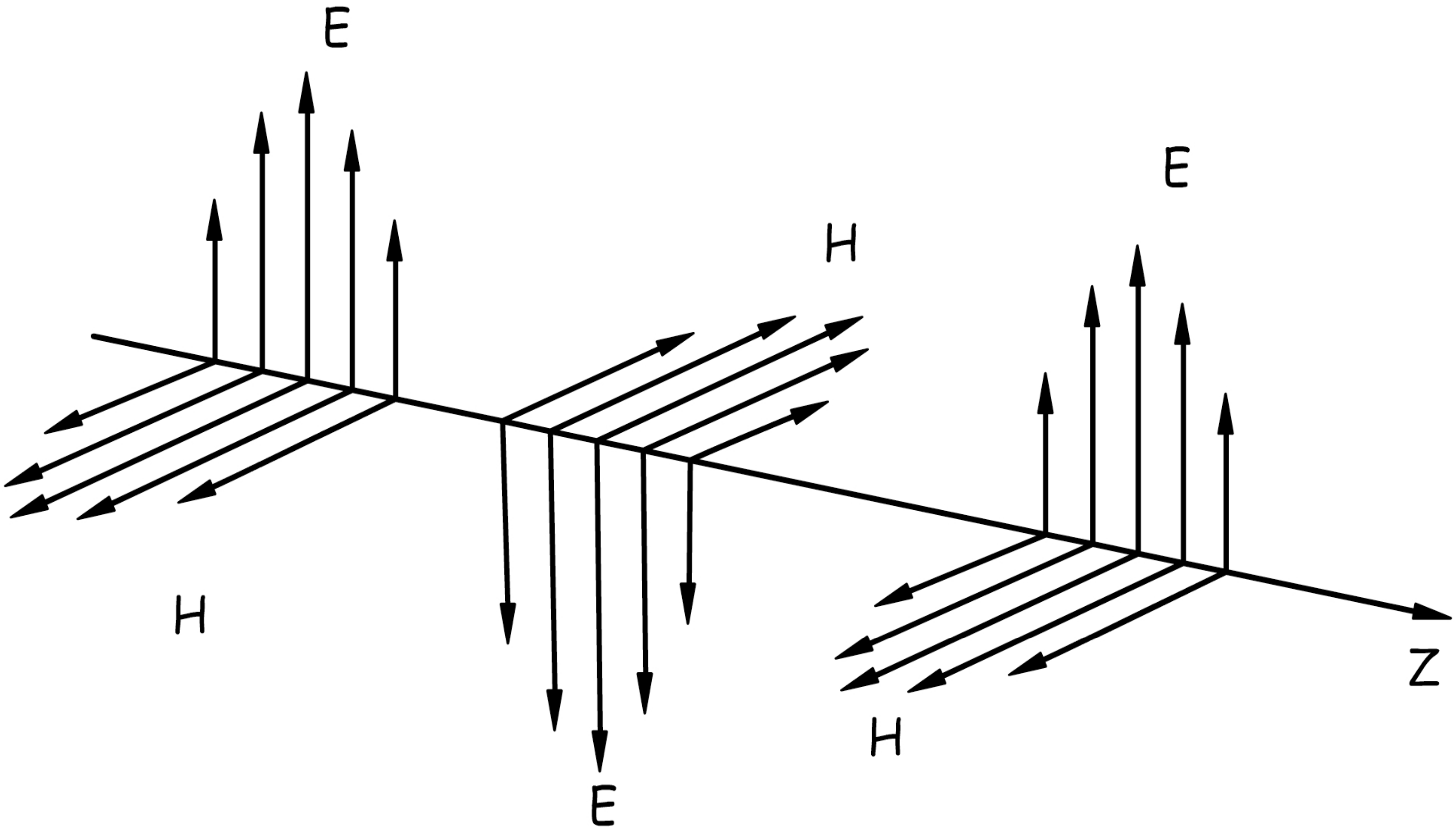


Polarization

- Polarization of a wave is the direction of the electric field vector
- Linearly polarized waves have the vector in the same direction at all times
  - Horizontal and vertical polarization are common
- Circular and elliptical polarization are also possible



circular polarization



Linear polarization

Cross Polarization

- If transmitting and receiving antennas have different polarization, some signal is lost
- Theoretically, if the transmitting and receiving polarization angles differ by 90 degrees, no signal will be received
- A circularly polarized signal can be received, though with some loss, by any linearly polarized antenna

Refraction

- Occurs when waves move from one medium to another with a different propagation velocity
- Index of refraction *n* is used in refraction calculations

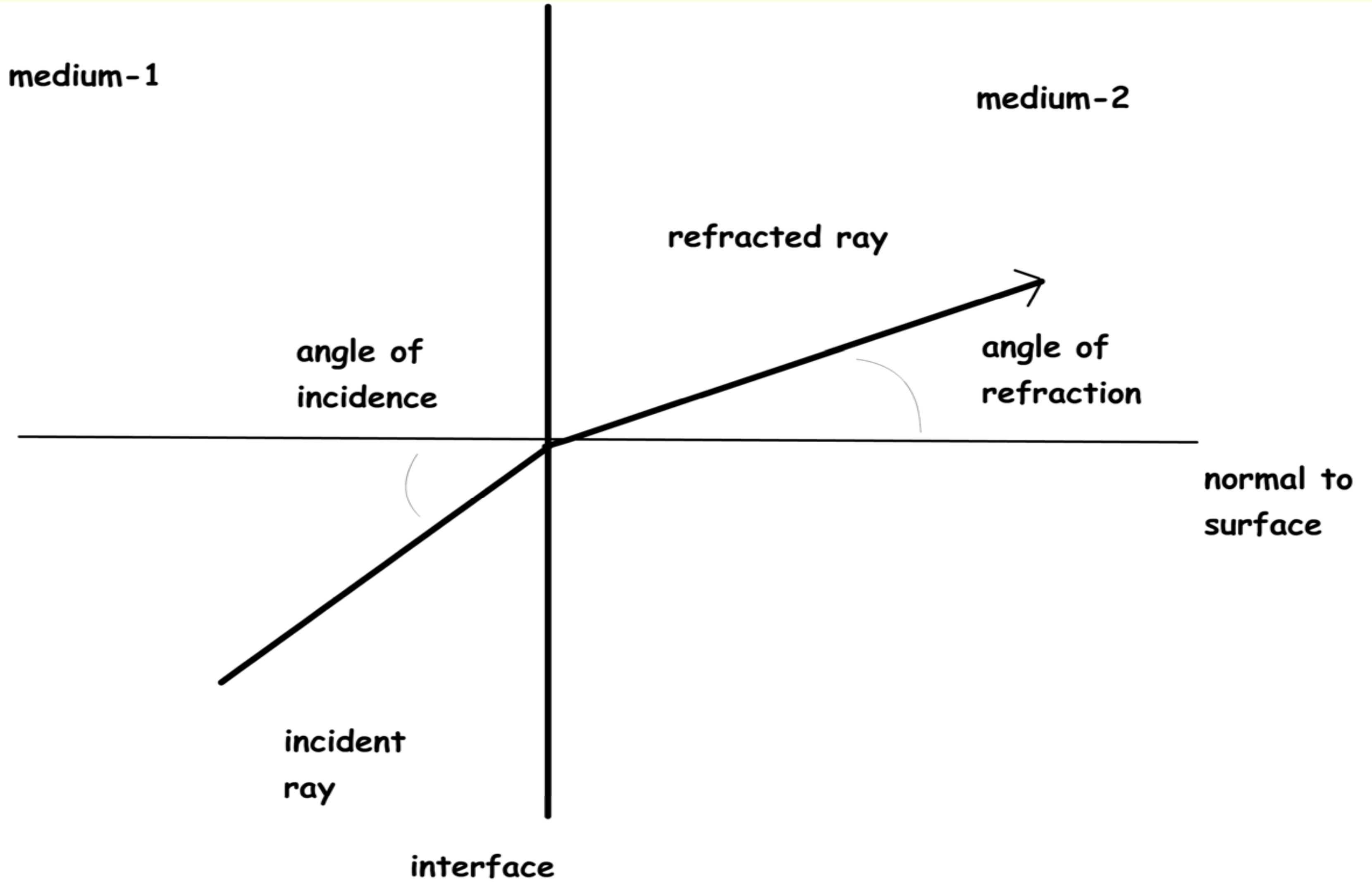
$$n = \sqrt{\varepsilon_r}$$

Snell's Law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- Angles are measured with respect to the normal to the interface

Refraction


medium-1
medium-2
refracted ray
angle of incidence
angle of refraction
normal to surface
incident ray
interface

Losses

- Geometric (if the wave is not a plane wave)

- Reflection and refraction

- Scattering

- Defocusing surfaces

- Polarization

- Absorption

Relation of dispersion

Relation of dispersion is an equation able to describe the behaviour of a radio wave in the media. This is obtained by inserting the wave solution in the last two Maxwell's equations. Let's consider a plane wave written in terms of complex exponentials

$E=E_{max}e^{j(\omega t- kx)}$

Introducing it in the third after easy derivation we obtain:

Relation of dispersion

$$-ikE_{0x}e^{i(\omega t-kz)}=-i\omega B_{oy}e^{i(\omega t-kz)}$$

The above divided by $E_{0x}e^{i(\omega t-kz)}$ furnishes:

$$\frac{B}{E}=\frac{k}{\omega}$$

The same operation on the fourth of the Maxwell's equations will furnish:

$$\frac{B}{E} = \frac{(i\omega\mu\varepsilon + \sigma\mu)}{ik}$$

Equating the last two we obtain:

$$k^2 = \omega^2\mu\varepsilon - i\omega\sigma\mu$$

This is the relation of dispersion.

$$\begin{cases} k_r^2 + k_i^2 = \mu\varepsilon\omega^2 \\ 2k_r k_i = \mu\sigma\omega \end{cases}$$

$$k_r = \frac{\omega}{c}\sqrt{\frac{\varepsilon_r\mu_r}{2}}\sqrt{\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1}$$

$$k_i = \frac{\omega}{c}\sqrt{\frac{\varepsilon_r\mu_r}{2}}\sqrt{\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1}$$

Once again the wave function

$$E = E_o e^{j(\omega t - kx)}$$

Knowing that k is a complex quantity one can write:

$$E = E_o e^{-kix} e^{j(\omega t - krx)}$$

The imaginary part of k contributes to the exponential absorption while the real part of k describes the oscillating wave.